NASA/TM-2003-

Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4, Volume III:

Radiometric Measurements and Data Analysis Protocols

James L. Mueller, CHORS, San Diego State University, San Diego, California
Giulietta S. Fargion, Science Applications International Corporation, Beltsville, Maryland
Charles R. McClain, Goddard Space Flight Center, Greenbelt, Maryland

J. L. Mueller
CHORS, San Diego State University, San Diego, California
Andre Morel
Laboratoire d'Oceanographie, Universite Pierre et Marie Curie, Villefranche-sur-Mer, France
Robert Frouin
Scripps Institution of Oceanography, University of California, San Diego, California
Curtiss Davis
Naval Research Laboratory, Washington, District of Columbia
Robert Arnone
Naval Research Laboratory, Stennis Space Center, Mississippi
Kendall Carder, Z.P. Lee, and R.G. Steward
University of South Florida, St. Petersburg, Florida
Stanford Hooker and Brent Holben
NASA Goddard Space Flight Center, Greenbelt, Maryland
Curtis D. Mobley
Sequoia Scientific Inc., Redmond, Washington
Scott McLean
Satlantic Inc., Halifax, Nova Scotia, Canada
Mark Miller
Department of Applied Science, Brookhaven National Laboratory, Upton, New York
Christophe Pietras and Giulietta S. Fargion
SAIC General Sciences Corporation, Beltsville, Maryland
Kirk D. Knobelspiesse
Science Systems and Applications, Inc., Greenbelt Maryland
John Porter
School of Ocean & Earth Science & Technology, University of Hawaii, Hawaii
Ken Voss
Physics Department, University of Miami, Florida

National Aeronautical and
Space administration

Goddard Space Flight Space Center
Greenbelt, Maryland 20771

January 2003

Chapter 3

Above-Water Radiance and Remote Sensing Reflectance Measurement and Analysis Protocols

James L. Mueller[1], Curtiss Davis[2], Robert Arnone[3], Robert Frouin[4], Kendall Carder[5], Z.P. Lee[5], R.G. Steward[5], Stanford Hooker[6], Curtis D. Mobley[7] and Scott McLean[8]

[1]*Center for Hydro-Optics and Remote Sensing, San Diego State University, California*
[2]*Naval Research Laboratory, Washington, District of Columbia*
[3]*Naval Research Laboratory, Stennis Space Center, Mississippi*
[4]*Scripps Institution of Oceanography, University of California, San Diego, California*
[5]*University of South Florida, St. Petersburg, Florida*
[6]*NASA, Goddard Space Flight Center, Greenbelt, Maryland*
[7]*Sequoia Scientific Inc., Redmond, Washington*
[8]*Satlantic Inc., Halifax, Nova Scotia, Canada*

3.1 INTRODUCTION

As an alternative to the in-water methods of Volume III, Chapter 2, water-leaving radiance can be measured from the deck of a ship. A shipboard radiometer is used to measure radiance $L_{\mathrm{sfc}}\left(\lambda,\theta,\phi\in\Omega_{\mathrm{FOV}};\theta_{\mathrm{o}}\right)$ emanating from the sea surface at zenith angle θ (usually chosen between 30$^{\mathrm{o}}$ and 50$^{\mathrm{o}}$) and azimuth angle ϕ (usually chosen between 90$^{\mathrm{o}}$ and 180$^{\mathrm{o}}$ away the sun's azimuth ϕ_{o}). In the convention used here, azimuth angles ϕ are measured relative to the sun's azimuth, *i.e.* $\phi_{\mathrm{o}} = 0$.

The surface radiance measured with a radiometer having a solid-angle field of view (FOV) of Ω_{FOV} sr may be expressed, following Mobley (1999), as

$$L_{\mathrm{sfc}}\left(\lambda,\theta,\phi\in\Omega_{\mathrm{FOV}};\theta_{\mathrm{o}}\right)=L_{\mathrm{W}}\left(\lambda,\theta,\phi\in\Omega_{\mathrm{FOV}};\theta_{\mathrm{o}}\right)+\rho L_{\mathrm{sky}}\left(\lambda,\theta_{\mathrm{sky}},\phi_{\mathrm{sky}}\in\Omega'_{\mathrm{FOV}};\theta_{\mathrm{o}}\right). \tag{3.1}$$

$L_{\mathrm{W}}\left(\lambda,\theta,\phi\in\Omega_{\mathrm{FOV}};\theta_{\mathrm{o}}\right)$ is water-leaving radiance centered at angles (θ, ϕ) and averaged over Ω_{FOV} [as weighted by the radiometer's directional response function (see Volume II, Chapters 2 and 3)]. $L_{\mathrm{sky}}\left(\lambda,\theta_{\mathrm{sky}},\phi_{\mathrm{sky}}\in\Omega'_{\mathrm{FOV}};\theta_{o}\right)$ is sky radiance measured with the radiometer looking upward at angles (θ_{sky}, ϕ_{sky}). In practice, θ and θ_{sky} are numerically equal angles in the nadir and zenith directions, respectively, and the sea and sky viewing azimuths $\phi = \phi_{\mathrm{sky}}$. The reflectance factor ρ is operationally defined as the total skylight actually reflected from the wave-roughened sea surface into direction (θ,ϕ) divided by sky radiance measured with the radiometer from direction (θ_{sky},ϕ_{sky}), both quantities being averaged over Ω_{FOV} (Mobley 1999). Remote sensing reflectance is then determined, using water-leaving radiance calculated from (3.1), as

$$R_{\mathrm{RS}}\left(\lambda,\theta,\phi\in\Omega_{\mathrm{FOV}};\theta_{o}\right)=\frac{L_{\mathrm{W}}\left(\lambda,\theta,\phi\in\Omega_{\mathrm{FOV}};\theta_{o}\right)}{E_{\mathrm{S}}\left(\lambda;\theta_{\mathrm{o}}\right)}, \tag{3.2}$$

where $E_{\mathrm{S}}(\lambda;\theta_{\mathrm{o}})$ is incident spectral irradiance measured above the sea surface. All of the above variables vary with solar zenith angle θ_{o}.

A simplified notation is used in Volume III, Chapter 2 (and elsewhere in the protocols) when discussing water leaving radiance $L_{\mathrm{W}}(\lambda)$ and remote sensing reflectance $R_{\mathrm{RS}}(\lambda)$ derived from in-water profile measurements of $L_{\mathrm{u}}(z,\lambda)$. Because $L_{\mathrm{u}}(z,\lambda)$ is measured in water viewing the nadir direction, $L_{\mathrm{W}}(\lambda)$ represents radiance leaving the surface in the zenith direction (θ, ϕ) = (0$^{\mathrm{o}}$, 0$^{\mathrm{o}}$). Therefore, $L_{\mathrm{W}}(\lambda)$ in, *e.g.*, Volume III, Chapter 2 corresponds to $L_{\mathrm{W}}\left(\lambda,0,0\in\Omega_{\mathrm{FOV}};\theta_{\mathrm{o}}\right)$, and $R_{\mathrm{RS}}(\lambda)$ to $R_{\mathrm{RS}}\left(\lambda,0,0\in\Omega_{\mathrm{FOV}};\theta_{\mathrm{o}}\right)$, in the present notation .